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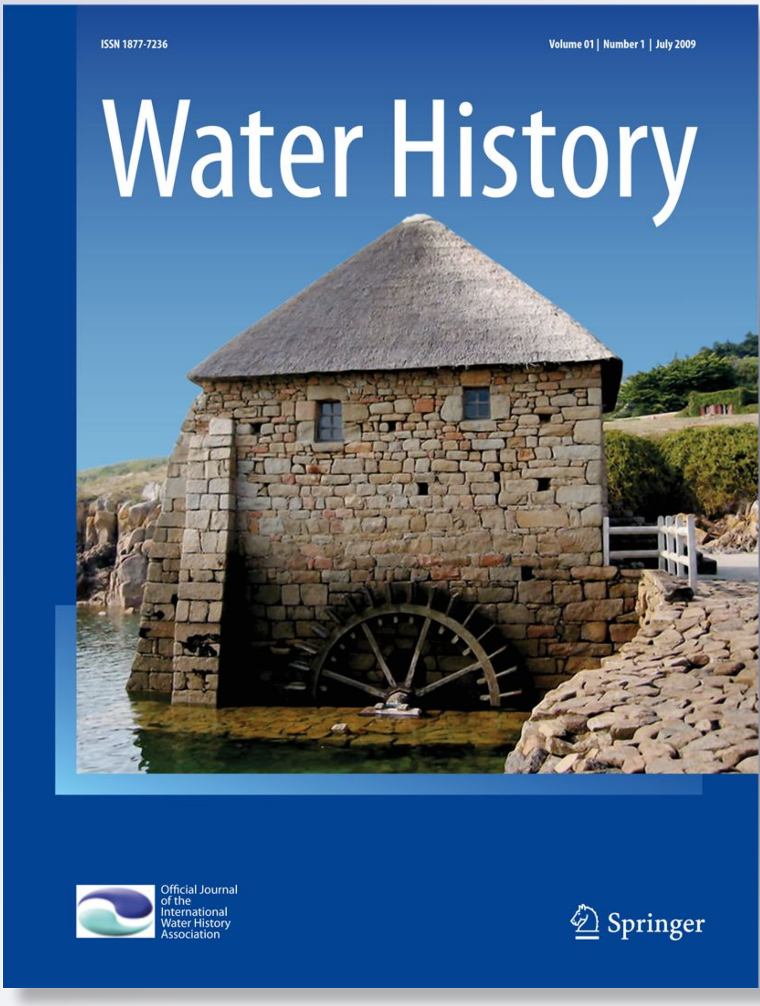

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The role of historical sources in the functional representation of a river in the new world. The case of the Argentinian Paraná

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Abstract How can we understand and construct a New World with European benchmarks that do not necessarily apply in this environment? In order to discover and appropriate a territory, its nature must be touched. Therefore, the body of the Paranà river has changed, with the scars of territorial colonisation remaining today. We can then ask how different cartographies represent the fluvial dynamics of a New World river and how the maps lead to the identification of this change. By adopting a global framework across the Argentinian Paraná, we seek to identify changes in the river dynamics. The geohistorical approach using old maps gives a new representation of the Paraná river. Our archive research allowed us to collect 60 maps depicting a period covering the fifteenth to the twentieth century. The scales of analysis also vary: the maps show the Paraná from its regional integration (1/100,000) up to a continental scale (1/18,500,000). The validation of the cartography is performed by comparing the representations with descriptions of the river found in texts dating from the same period. The methodology used is a map-to-map comparison, following the theory of river systems (Schumm 1977), in which sandbanks, islands and river planforms are considered to be markers of the river dynamics. The maps thus provide an answer: it is possible to trace the causes from the results. The causes are themselves related to spatial and climatic phenomena. Early maps show a braided planform in the upper reach of the Paraná and a Paraguay channel free of deposits. The current dynamics indicate an inversion in sedimentary transportation and deposit. The deforestation mechanisms in the Misiones territory and their abandonment could lead to a shift in the sediment load. This hypothesis will be demonstrated through analysis of the maps, its validation by texts and the results of a field studies.

Keywords Paraná river · Old maps · Geohistory · Geomorphology · Fluvial system · Sediment load

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Introduction

This work develops the advantages of using old maps in geomorphological studies of large, alluvial rivers. The Paraná river, the fifth largest river system in the world (discharge rate of 16,800 m^3/s at its mouth) has a typical mega-river functioning (Latrubesse and Amsler 2009). When the river was first discovered, the settlers faced a foreign unknown nature. The texts recounting this discovery refer to the known hydrology of European rivers, which are of much smaller dimensions (Azara 1998; Pelletier 2009). Therefore, using the images often offers more meaning than using the texts. From the mid-seventeenth century mapping techniques become sufficiently efficient to reflect the reality of the land. One can then ask what the antiquarian cartography can bring to present-day geomorphologic studies. We have chosen to analyse these contributions in terms of river dynamics. Indeed, even today the functioning of mega rivers is poorly known. The information extracted from old maps tells us about the mechanisms of the river over a much longer timescale than that usually employed (400 years instead of the 100 years of conventional studies).

This presentation is taken from a PhD thesis which incorporates this information into a larger set of problems. Entitled "*The Paraná River, a River of the New World*", this thesis highlights the appropriation and development of a gigantic spatial object by a society which stems from European emigration. The migrants must then cope with new benchmarks, with the discovery of the New World leading to the appropriation and regional development of the natural environment. The body of the river has changed and today the scars of territory colonisation can be seen. The maps, in their own diachronic, lead to the identification of these changes. The development of knowledge of the Paraná river and its appropriation is important in a country like Argentina. With its direction and course into Latin America over 4,000 km, the Paraná river is a fantastic gateway to enter and leave the New World. Its geographical position reminds us of those of St. Lawrence and Mississippi, although the development of their waterways is very different.

However, common features appear in the first uses of these mega rivers. The best example is probably the use of the natural waterway to discover and conquer the subcontinent. In fact, sailing and steamboats led to the recognition and development of the countries sharing this vast watershed (3.2 million square kilometers divided between Argentina, Bolivia, Paraguay, Brazil and Uruguay). To maintain some consistency in the set of problems and to reduce the size of the study area, the framework will be centred on the course of the Argentinian Paraná river (from the Iguazú Falls to the Plata river) (Fig. 1).

Presenting an original approach, the aim of this work is to determine the modifications to the river dynamics engendered by the appropriation of a new territory. We have chosen to cross the geohistorical and geomorphological analysis. This approach allows us to use any sorts of documentation, ranging from the historical maps from the XVIth century up to current satellite images (Landsat TM 2009). The scales of analysis are also varied: the old maps represent the Paraná river from a regional scale (1/100,000) to a continental one (1/18,500,000).

The methodology used follows a deductive approach, comparing the maps with each other. This approach also follows the theory of river systems, which binds the functioning processes and the responses of the river on the watershed scale (Schumm 1971, 1977). The sandbars and the planform of the river are considered markers of river dynamics. The maps are therefore a response: it is possible to trace the causes based on the results. The causes are related to the spatial and climatic phenomena. Early maps show a braided pattern on the upper Paraná river, with the Paraguay rivers at the same time seeming to be free of any deposit. The present fluvial dynamics indicate an opposite pattern.

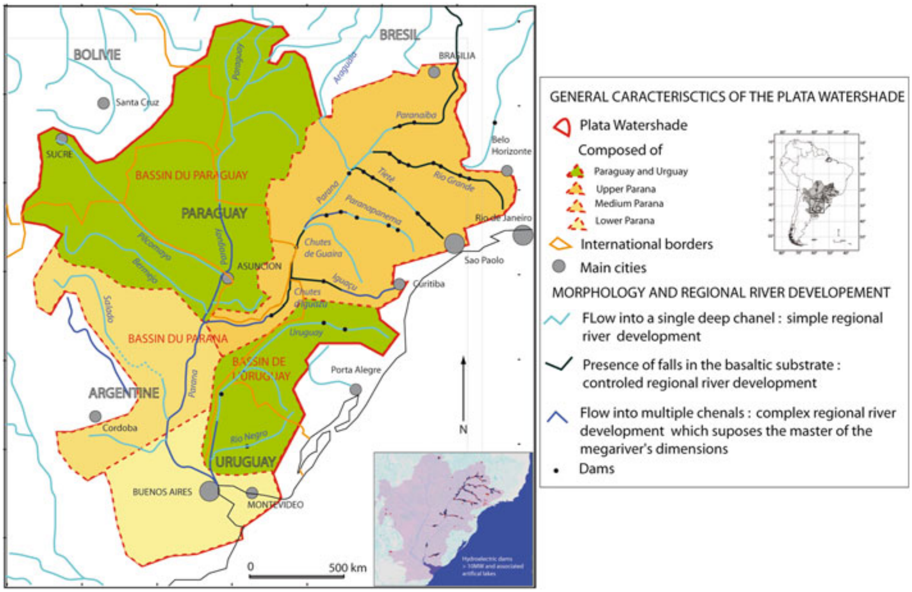


Fig. 1 General map of the Paraná river watershed

This work is thus built around the following problems: is it possible to enrich the current research concerning the functioning of the river with the information passed on to us from the old maps? Does the ancient cartography give us new keys to the understanding of the socio-fluvial dynamics using a longer timescale?

To answer these questions, in the first part we shall develop the assets of old cartography in the analysis of an enormous space. We shall then detail the necessary precautions in the use of old documents. The third part of the article shows how the ancient maps help to identify the changes in the river's morphology, by developing the example of the Upper Paraná river.

Finally, in the last part, we shall validate these hypotheses by describing the necessary research to be conducted in order to complete the demonstration.

The assets of ancient cartography in the analysis of an enormous space over a long timescale

Our searches conducted in the archives of European cities (Paris, London, Madrid, Seville, Simancas) and Argentinian ones (Buenos Aires, Santa Fe, Corrientes) enabled us to assemble 60 maps depicting a period spanning five centuries (from the sixteenth century until 1932). Despite the large quantity of maps in our possession, the collected corpus imposes certain limits, as the method of analysis is based on the examination of old maps. The fundamental data are provided by these documents. Therefore, the spatial scale of the study is limited by the accuracy of ancient representations, itself conditioned by the scale of representation. Figure 2 symbolises the relationship between the production date and the scale of the maps. It integrates all the maps on which the scale is clearly indicated. When the scale is not reported it is difficult to determine, due to the common projection and

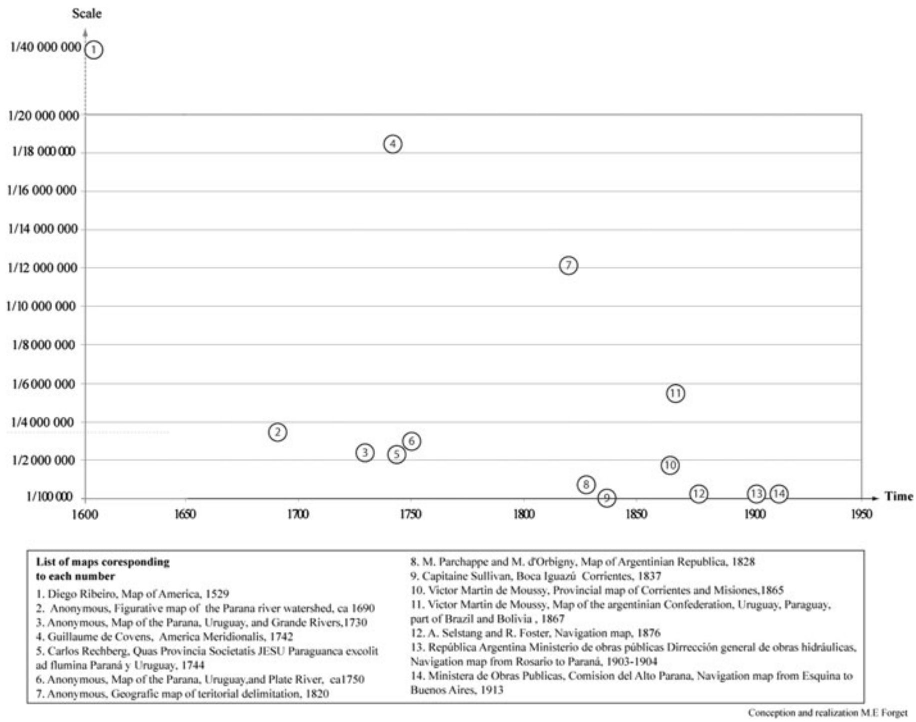


Fig. 2 Map scale against time

location errors. The corpus of documents includes a range of representations from very small-scale (1/40,000,000) to large-scale plans (1/10,000). This figure shows that small-scale maps, still used in the late nineteenth century, tend to be replaced by larger-scale maps. It is also noted that the cartography, from the late seventeenth century until the middle of the eighteenth century, represents the small-scale watershed (between 1/3,500,000 and 1/2,000,000). A century later, the majority of production is on a scale of around 1/100,000, with the gradual emergence of accurate navigation plans on a 1/10,000 scale.

The topographic style in cartography which appears in the sixteenth century in Europe (Broc 1986) only represents the well-known territories at this time. For the rest of the world, after a short period that ended around 1540–1550, there is a progression from the stage of mere recognition to that of real exploration and colonisation. Changes in representation demonstrate greater knowledge of the territory. The corpus of documents is rich in terms of interlocking scales, but also takes into account the entire watershed, which is relatively rare in the current studies.

The corpus of maps also determines the period of analysis. Just like the land area covered by the cartography, the time frame of the study differs from the one currently used. Whereas geomorphological studies recently began to work on a time scale of a century, old maps show us around 400 years. The first known map of the Paraná river is Sebastien del Cano's map dating from 1523, and the final map taken into acount is a Map of Navegacion (*derotero*) dated 1932. However, there are gaps in the temporal coverage of the study area (Fig. 3). During certain time intervals, no maps were produced (1500–1530, 1540–1560,

1580–1620, 1640–1660, 1710–1730, 1760–1780 and lastly, 1890–1910). It is possible that these time intervals represent gaps in the archives or that some periods are less suitable for spreading cartography. After the maps dating back to the discovery, production faded out then stagnated between 1830 and 1710, with an average of one map every 10 years. Figure 3 also shows the great enthusiasm held for the New World from the early nineteenth century.

To start with, such a rich corpus of documents is a challenge in itself. However, the documents are not of equal scientific value. They cannot be used without a review of their origin, their implementation, their purpose and the quality of their production. Analysis of the corpus shows its richness and allows us to circumvent its pitfalls.

Richness and pitfalls of old maps

These documents, based on different objectives and methodologies, offer a rich representation of the territory with good graphic qualities (Bravard 1989, 2011). Primarily, the historical maps represent the region's major rivers (Plata, Paraná, Paraguay and Uruguay rivers). Indeed, these are easy axis of communication enabling penetration deep into the continent. Most of these maps have never been used in any scientific work on the functioning of the Paraná river. In this article, we try to extract the qualitative and pseudo-quantitative information providing new evidence of the past dynamics of the Paraná river.

It must be stressed that the corpus of maps is of unequal value. The maps have a variable level of accuracy and reliability. The information provided depends on the mode of representation, which is often a consequence of the production period. Some representations can provide only qualitative data. To be used, most of the old maps must be supported by texts from the same period, in which we find the description of the region represented. The corpus has then been sorted through, based on the mode of representation

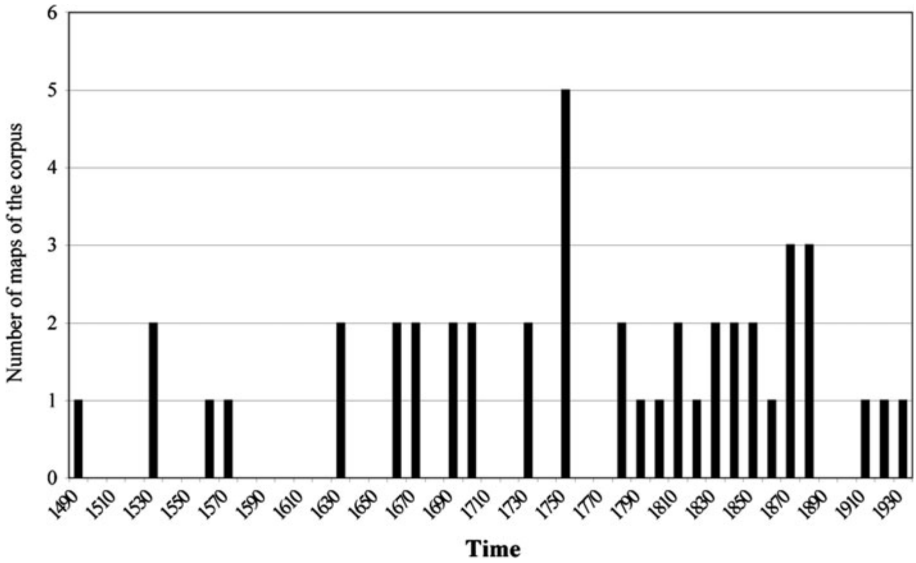


Fig. 3 Number of antique maps from the corpus produced by decade

and on the map reliability. The maps reflect the work of cartographers whose working methods varied; indeed, the maps produced between the sixteenth and nineteenth centuries are not necessarily the result of the work of professional cartographers, but may also be the work of amateur cartographers, travellers, explorers, sailors or settlers, who have not been trained in the techniques of ground survey or cartography (Broc 1986, 1999). Furthermore, the information drawn on the maps also depends upon the interests of the cartographer, the purpose of the map and the fluvial knowledge of those who made notes and sketches. In the field, the cartographers generally note what is important to them and what they know to be important. On the other hand there are also many study cartographers who compile information for mapping regions where they have never set foot. Their representations therefore are based only on secondary sources and do not verify the information by any field study. The maps thus produced, of varying quality, also have modes of representation and semiotic codes of their own (Pelletier 2001, 2009). To use them properly, their reliability must be determined to exploit the elements represented.

Nine maps from the sixteenth century reached the corpus. The first map produced in the territory of the Paraná river is attributed to Juan Sebastian del Cano (Fig. 4), representing the east coast of Uruguay and Argentina, and is dated 1523. Hydrography is symbolised here. It should be noted that the Paraná, Paraguay and Uruguay rivers are represented in an obvious way. Their layout is still rough but the representation shows the Uruguay flowing from north-east to south, well apart from the Paraná river which flows from north to south. The sharp bend in the Paraná river at Corrientes city has not yet been identified. It is interesting to see that the confluence of the Iguaçu river with the Paranáíba river is clearly recognised. The course of the Paraguay river and its confluence with the Paraná river are relatively well represented. Sebastian del Cano had to obtain this information from indigenous peoples. In its representation of the land, he commits a location error, as on the map, the river comes from the west and not the east. This proves that the map has not been established by field surveys. Indeed, although the survey techniques of that time are unclear, this is the kind of mistake that cannot be committed if the data recorded from natives are verified on the field.

The information provided by old maps therefore includes a number of errors, resulting both from incorrect knowledge and technical errors. Four old maps from this period are presented hereafter (Figs. 4, 5, 6 and 7) in order to determine the reliability of the representations. The phenomena of copying is quite common between the sixteenth and nineteenth centuries, particularly in areas of the world being discovered. A quick comparison of Figs. 4, 5, 6 and 7 shows that the representational errors propagate from one map to the next. For example, the drawing of the Paraná river between the maps of del Cano and that of Diego Ribeiro produced 40 years later is almost identical.

The scientific validity of the maps is then to be determined. To do so, the information shown on the maps is compared, confirmed or refuted by the contemporary literature. Many written sources exist, which complement the graphical information. The knowledge of the area is then often used and often written by conquistadores and travelers who describe their journey on the Parana. It is only at the begining of the XVIIIe, that the scientific descriptions of the banks of Parana inform us more both on the river functioning and on the natural environment represented on the maps. Among the most famous, we must cite Ulrich Schmidl (1544), Parish (1839), Alcide d'Orbigny (1845), Thomas Page (1859), Victor Martin de Moussy (1864) and Knight (1866). These texts were important for the interpretation of the maps. Confronting the image and the text enabled us to determine if the information represented on the map really suited the reality of the field. It is not always the case. Some informations on the old maps seem to have been copied from older maps

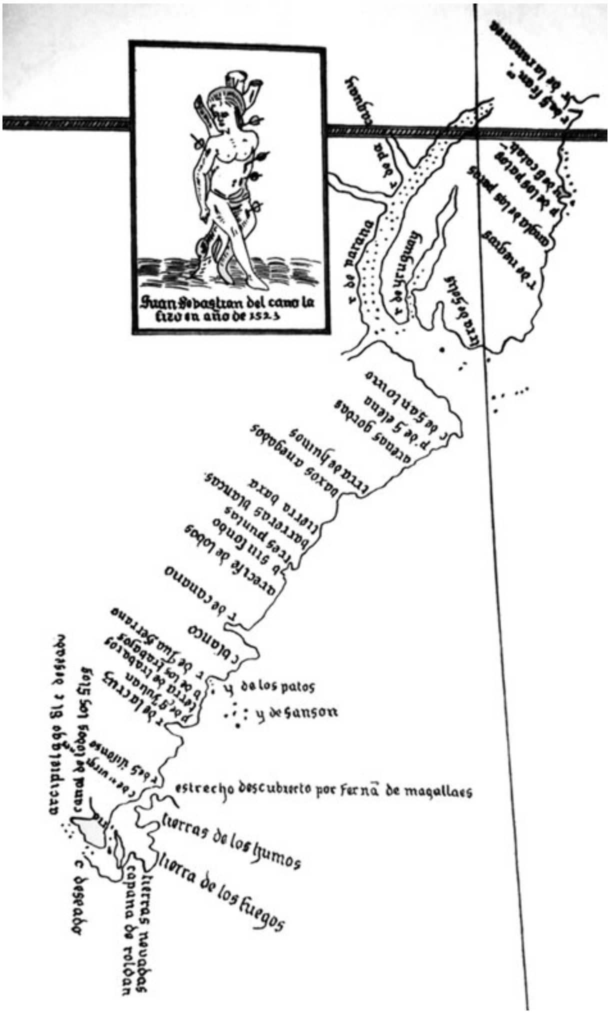


Fig. 4 East coast of Uruguay and of the Plata river basin in Juan Sebastian del Cano, ca. 1523. Dr. Buenaventura Caviglia's Personal collection

and therefore the representations lack precision and generally pass on erroneous informations. Furthermore, the texts allow us to confirm the planform of the river, in particular regarding localisations of the most important islands and sandbars in the channel. With the phenomena of copying and the weaknesses of the cartography, geoforms in the channel are indeed often badly localised, which distorts the impression given by the maps. We can, for example, quote Charles Knignt's papers, who describes exactly his journey on the river by giving the distance of the route between the various stops. More, his description of the landscape of the banks and the islands allowed us to recognise the environment on the maps and to determine the reliability of the river planform represented on the XVIIIe maps.

To simplify the process of validating the quality of the information, we propose a table of reliability of the different maps of the corpus (Table 1). As it is difficult to represent all the maps, we chose in the corpus of documents, nine maps, which can be considered

Fig. 5 Map of Plata river by Gaboto, 1544, gallery of Whitehall Palace, London

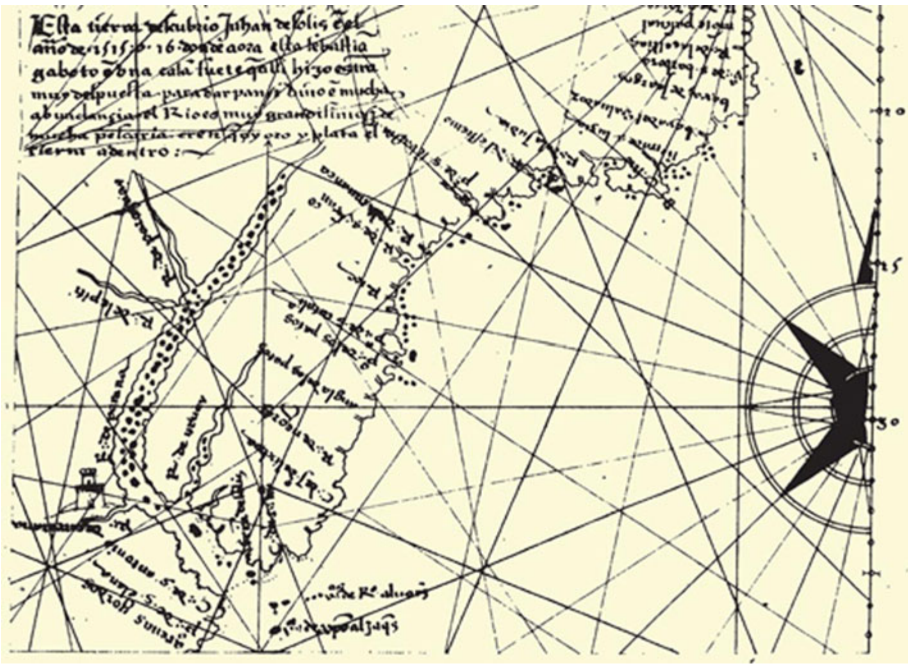


Fig. 6 Map of Diego Ribeiro, 1529, Vatican Apostolic Library

Fig. 7 Map of the Western Hemisphere, Diego Gutierrez, 1567, Rosenwald Collection, Library of Congress, no. 1303

representative of the evolution of the cartography from the XVIth to the XIXth century. These maps have been compared with texts of the same period in order to validate the indicators represented on the maps. We then can propose a table showing the aparition of the different indicators and their validity. In this table, we have represented the partially controlled elements in light grey, whereas when the element are well represented they obtain a darker grey. It then appears that it is only at the end of the XVIII that all of the indicators are totally controlled by the cartography. Before 1865, the indicators are not complete but the knowledge of the river builds itself little by little, with headways and recessions according to the objectives and the information that reached the cartographers. This table shows a trend of reliability that can be applied to the different periods. However, the old maps have to be analysed on a case-by-case basis. The appearance of navigation plans marks the separation between the corpus of ancient documents and the modern ones; the 1920s can be regarded as the turning point.

The cartographic data produced is more significant over the eighteenth and nineteenth century. The evolution in the representation of the Earth's surface, and the progress of cartography, give a better idea of river morphology. Several observations can be made taking Figs. 8, 9, 10 and 11, for example.

Figures 8 and 9, dating from the late seventeenth century, represent the Plata river on a comparable scale. Analysis of the two representations shows that the mistakes from the previous century continue to spread. Figure 9 does not identify the change to the east of the Paraná river's direction. The river's route is approximate, as are the distances between the Paraná Delta and the confluence with the Paraguay river. However, Nicolas Sanson d'Abbeville's map is of a high precision in the drawing of the course of the river and its

Table 1 Degree of reliability that can be attributed to the graphical data within the corpus

Texts that have been compared to the content of the maps	Pierre-Martyr d'Anghiera, 1493-1525 Ulrich Schmidl, *1554*		G. Echaurri, 1739				Bravet, 1768	d'Orbigny, A., 1826-1833 Parish, W., 1839 Hinchliff, T. W., 1863 Knight, C. 1866	
Old maps / Indicators that coincide between the texts and the maps of reference	Sebastien Cano 1523	Vincente Cafara 1665	Anonymous 1722	Carlos Rechberg 1744	Padre Jose Quiroga 1749	José Cardiel 1752	Cano y Medilla 1775	Anonymous 1826	Victor Martin de Moussy 1865
								■	■
Validity of the cartographic projection									
Direction of flow in the Parana River		▒	▒	■	■	■	■	■	■
Cities/ village localization			▒	▒	▒	▒	▒	■	■
Planform of the river – Upper Parana			▒				■	■	■
Planform of the river – Middle Parana	▒	▒			■	■	■	■	■
Precise localization of the main islands							▒	■	■
Precise localization of the sandbars									■
Proportionality of the river width			▒	▒					■
Representation of the multiples channels							■	■	■
River system hierarchy			▒				■	■	■
Tributary rivers		▒	▒		▒		■	■	■

■ Totaly controled element ▒ Partialy controled element

Fig. 8 Paraguay divided up into its main parts, Nicolas Sanson d'Abbeville, 1665, Bibliothèque Nationale de France

Fig. 9 Map of Paraguay and neighbouring countries, ca. 1700, Anonymous, personal collection

morphology. It should be stressed that originally Sanson d'Abbeville is known to be a study geographer. Figures 10 and 11, dating from the early eighteenth century, are similar to Sanson d'Abbeville's representation. They were, however, produced by people who know the area well. Figure 10, for example, was designed by a Jesuit priest, aiming to locate the various Jesuit missions of Argentinian and Paraguayan territories. Particular attention is paid to the river, which is the only means of communication between the different missions and settlements at this time (de Massy 2010; Levington 2007, 2009). It is therefore possible to hypothesise that the curved line made by the Paraná river at the confluence with the Paraguay river found in Figs. 8, 9 and 10 corresponds to the actual river course at that time. Today the course of the river has changed; however, we found marks of a palaeochannel in the landscape. The maps combined with field work can then document changes in the river morphology.

How do old maps help to identify changes in the functioning of the Paraná river?

On all the old maps taken into account, the bed of the Paraná river is crowded with islands of different sizes. While the authors were unable to accurately represent the location of these islands, the information provided by this cartography allows the data quality to be examined. Indeed, this study comes into the framework of Schumm's river system theory (Schumm 1971, 1977). The sandbars and planform of the river are considered markers of the river dynamics.

To refine the analysis, it is necessary to select a reference map that allows comparison with the current map production. This comparison is established by creating a GIS with the

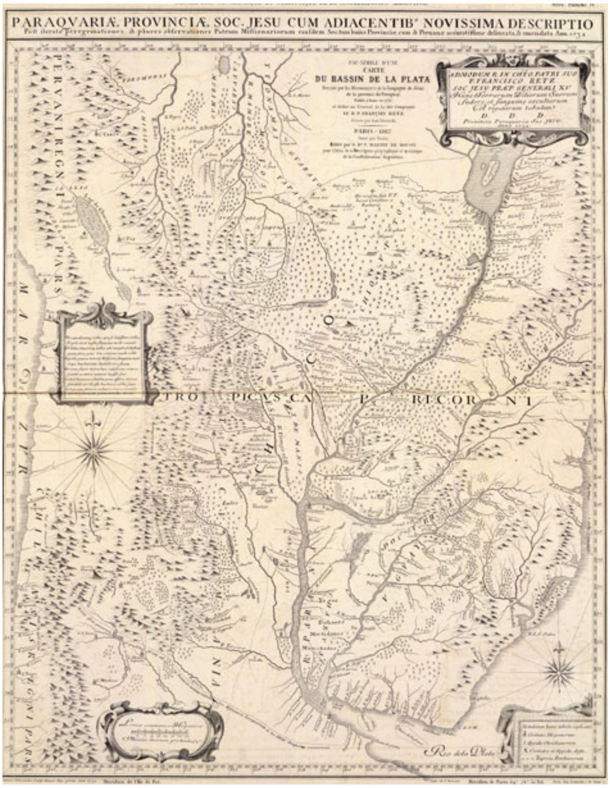


Fig. 10 Paraquariae provinciae Soc. Iesu cum adjacent. novissima post descriptio per egrinationes iterate, and multi Observationes Missionariorum ejusdem Patrum Soc. tum hujus provinciae, cum and Peruanae, Anonymous, 1722, Bibliothèque Nationale de France

software ArcGIS 9. All the old maps could not be georeferenced in this system because the projection methods are unknown or the localisation errors are too large. The result of attempting to georeference certain maps produced before the seventeenth century has been catastrophic. The images were unusable due to excessive distortion that makes them unreadable. We then selected from our corpus of documents the oldest and most accurate map supporting this type of treatment. The selected map dates back to the mid-eighteenth century. It comes from a book collection of a seminary within the Lyon region (France). It represents the Upper and Middle Paraná river. By this time the techniques and measuring instruments are sufficiently precise to allow a comparative analysis with the current data. The map also makes possible to distinguish the styles of different river stretches from the city of Ontivera at Salto Grande (present-day city of Itaipu) up to the present city of Buenos Aires (Fig. 1).

To give a specific example of the use of old maps and historical geography in geomorphological studies, we chose to analyse a stretch of the Upper Paraná river. The methods will therefore be applied to this stretch from Corrientes to Posadas, which successively features a single course cut into a basalt substrate, followed by a highly charged stretch which contains islands and sandbanks (braided pattern) up until the confluence with the Paraguay river (Fig. 1). From this point, the course changes direction and the river clears.

Fig. 11 Misiones Provincia Quas Societatis JESU Paraguanca excol ad flumina Paraná y Uruguay, Carlos Rechberg, 1744

The eighteenth-century map represents the Apipe falls that punctuate the main channel of the Paraná river. The presence of these rapids and rocky outcroppings led us to use topographic maps and satellite images produced prior to commencement of the works on the Yacyretá dam (1983) in order to diachronically compare forms of this river stretch (Fig. 12). The island of Apipe, easily recognisable on the map, confirms that the eighteenth-century cartography is very accurate. Indeed, this large island is not only well located, but also has a shape similar to the current form despite some changes that may be attributed to the river dynamics after the completion of the map. Based on these observations, we are therefore inclined to think that the location of the large islands is accurate. The scale of the map is not precise enough to represent all of the small islands in the main stream of the Paraná river. We have chosen to consider that the small islands presented with a circular form (less than 3 mm in diameter) are more likely to be sandy surfaces or subsurface deposits (Federzoni 2006; Gurnell et al. 2005; Hooke and Kaine 1982; Torre 1938). Indeed, the spatial accuracy of the representation is limited by the size of the map and by the scale of representation. Furthermore, the graphic semiology adopts a process of simplification and schematisation. The islands and sandy deposits appear to have been simplified: no current deposit is characterised by such circularity. At best, the islands and

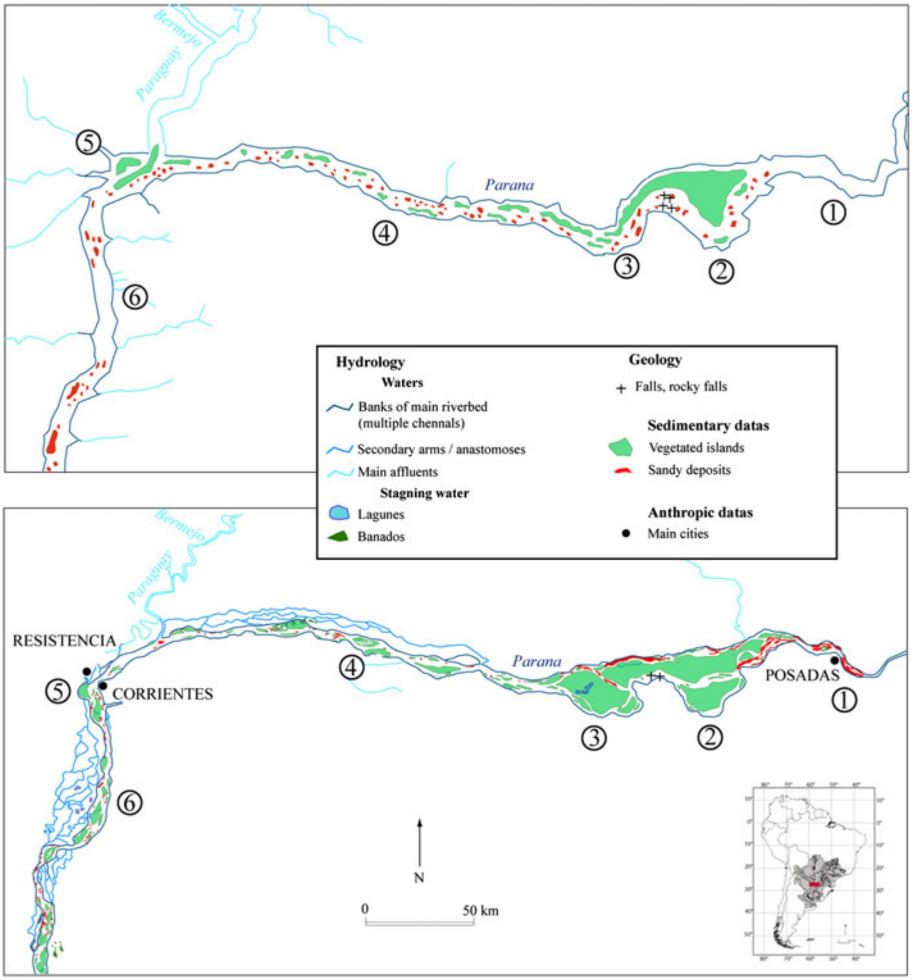


Fig. 12 Comparison of fluvial patterns of the Upper Paraná section, from the city of Corrientes (Corrientes) to the city of Posadas (Misiones), Argentina

deposits grow by an oblong geometry (Bonetto and Orfeo 1984; Peireira 2009). In contrast, the larger, more elongated islands seem to be relatively stable, and probably vegetated (Fig. 12).

To facilitate analysis we have chosen to number the sections with the most similarities and differences, the key point of the analysis being the fluvial pattern. Comparing the different sections allows us to examine the main changes that have affected the Paraná river over the past 250 years. We have identified six areas:

Zone 1 is located opposite the present city of Posadas. Today it is the capital of the province of Misiones but it does not appear on the eighteenth-century map. This area corresponds to the transition from a single-channel pattern to a mixed pattern (braided, anastomosing). The river begins to flow into multiple channels, a pattern that it keeps up to its estuary. No river metamorphosis has occurred in 250 years, with the two maps showing a flow in multiple channels. The functioning of the Paraná river seems to have remained

stable over a century timescale. The river flows into a hard sandy substrate where it has difficulty in adjusting its shape to possible changes in the flow conditions. The adjustment to the river would then preferentially spread to areas downstream. We can also consider that the hydrodynamic conditions in the eighteenth century allowed the transit of sediment without deposition. This would explain the lack of sandy deposits in the bed on the old map. Many mobile sand banks are present today, over a distance of 20 miles, sandy banks encumber almost all of the bed.

Zone 2 is the Apipe island area which retains its triangular shape. In the eighteenth century the island is pressed against the right bank of the Paraná river, where 250 years later a cluttering of the river bed has emerged. The channels can reach the number of four before the narrow part of the bed at the Apipe falls, where the Paraná river flows into a single channel. The island is vegetated, which stabilises its form (Hickin 1984; McCarthy and Ellery 1992; Smith 1981). An increase in its surface area can be observed upstream, with a secondary cut of a small channel.

Zone 3 also shows an adjustment zone, with marked widening of the Paraná river's main channel. The tail of the Apipe island has developed into a vegetated island, which separates the flow into three or four channels. Downstream from this island, other elongated islands exist that are already present in the Paraná river channel in the eighteenth century.

Zone 4 extends for about 200 km between the Apipe falls and the city of Corrientes. This section of the Upper Paraná river is characterised by a flow in multiple channels. Differences exist in the flow conditions between the two maps; it seems that the eighteenth-century map represents a main channel particularly loaded with islands or sandbars. The deposits seem to exist in larger quantity in the eighteenth century whereas the vegetated islands also appear to be relatively stable.

Zone 5 at the city of Corrientes precisely represents the shift of the Paraná river to the South after its confluence with the Paraguay river. This area appears to be a nodal point of the Paraná river. By 'nodal point' we mean an area which morphology has remained unchanged over a long period of time. Some changes appear between the old maps and the current maps, but they are scarce. The permanent anabranch located at the city of Resistencia is not yet represented on the eighteenth-century map.

Zone 6 is a section of the Paraná River where mutations are most noticeable. Over a short distance, the Paraná river crosses its floodplain to flow on the western margin of the alluvial plain between the towns of Goya and Esquina (110 km) before flowing again on its eastern margin. This section is represented on the eighteenth-century map as a section where no sand deposit has been identified. Today it is the most complex section of the area. The flow is divided into four channels coupled with four anabranches with perennial flow.

When analysing this area, we can present the following assumptions:

- Either the Paraná river has increased its sediment supply in this section that is has not been able to evacuate. Areas of aggradation have then been formed and stabilised by the establishment of vegetation in a context similar to the current climate.
- Or it has experienced a significant decrease in liquid flow, that no longer evacuates the downstream sediment load coming from the upstream watersheds.

Data obtained by comparing the maps over a timescale of several centuries show that some sections have experienced more changes than others on this 300 km stretch. Keeping in mind that the assumptions are based on a diachronic map analysis, it is possible to affirm that the fluvial style remains relatively stable at this spatial scale. On a larger scale, the stability is more relative. The river pattern adjusts to solid (Qs) and liquid (Ql) flows,

forming straight or braided sections. These change and experience transitions from one pattern to another.

We can then make the hypothesis that the present islands are the legacy of past river dynamics. It is therefore possible to understand to what the changes in the Paraná river's morphology are due. The key factors are surely climate change and land use, which have a direct influence on the liquid and solid flows of the Paraná river. Indeed, these factors that can explain a change of pattern.

Results and partial validation of hypothesis

The eighteenth-century map shows a braided pattern on the Upper Paraná river and a Paraguay river course free of any deposit. The current river dynamics suggest an inverse functioning, with rare depositions in the Upper Paraná river whereas the Paraguay river bed is loaded with sedimentary islands. Today, the Bermejo river, a tributary of the Paraguay river, provides around 80% of the Paraná river's sediment load (Amsler 1999, 2000, Amsler 2006, 2007; Bonetto and Orfeo 1984; Drago 1977; Drago and Amsler 1981; Itaipu 2006; Orfeo 1995; Pinto 2008; Ramonell 2008). On old maps, however, the river morphology downstream of the confluence suggests that very little sediment is coming from the Paraguay river. The clutter of the bed and the braided pattern in Sects. 1 and 4, suggest significant sediment transportation. It seems that in the eighteenth century, the sediment load comes preferentially from Argentinian Misiones, Paraguay and Brazil, which also coincide with the start of land clearing in the catchment area of Brazil. Furthermore, it is recognised that the Bermejo may have ceased to provide sediment for a certain period of time (Peireira 2009).

We believe that differences in river morphology can then be explained by using data on climate change recorded in the watershed, and by questioning the dynamics of the Jesuits territories. Land clearing in the Misiones territory could *de facto* cause a significant sediment supply through soil erosion. The abandoned fields after the expulsion of the Jesuits could then explain the shift in the origin of the sediment load.

The effects of climate change on the Paraná river morphology

The variables of control of the sediment load are the sediment supply and the capacity of the river system to carry this mobilised load. The climatic variations of the eighteenth and nineteenth centuries modify these variables depending on the temperature and precipitation in the different areas of the watershed. In a study conducted by Mr. Cioccale (1999), climate change since the thirteenth century is clearly stated. The precipitations tend to decrease during the Little Ice Age (LIA) dating from the mid-eighteenth century until the early nineteenth century (Cioccale 1999). Moreover, most stored sediments may have been exported before the LIA. In fact, from approximately 1,100–1,400 AD, the Argentine climate is characterised by a warm and humid climatic optimum (Riccardi 1995). The increase in precipitations and the development of the river systems triggered the draining of the available sediment (Carignano 1997). The LIA episode appears in the sedimentary records (De Blij and Muller 1993; Latrubesse 1990) and in the historical records (Furlong 1937; Prieto and Jorba 1990) in the late Middle Ages as colder, drier conditions (Cioccale 1999; Iriondo and Krohling 1995; Iriondo and Garcia 1993). Some tributaries of the current Paraná river, such as the Salado, were disconnected from the system. The cartography from the Jesuit period (Furlong 1937) shows significant changes in the river systems (reduced

length of active streams, channel changes, bifurcations) and the decrease or disappearance of lakes and wetlands. In general, climatic pulsations do not affect riparian areas of the Paraná river in the same way. The river systems of the left bank of the Paraná river seem to have spread during cold periods, always benefitting from a subtropical climate, whereas the fluvial systems of the right bank shrunk drastically (Cioccale, 1999). Thus, the sediments are more easily transported from the Northeast watershed than from the Andes Cordillera, contrary to what is observed nowadays. Climate characteristics then seem to confirm the hypothesis that the Upper Paraná provides a higher sediment load than the one provided by the Paraguay river.

Deforestation as a factor in the sediment load change

The differential climate changes in the watershed thus generate different climatic conditions in the different parts of the basin. We have just seen that the provinces of the Northwestern Paraná watershed received more precipitations that may have caused erosion of the soils. These physical data should be cross-referenced with human data, which act in the same direction. In fact, during this period (eighteenth and nineteenth century), the provinces of Misiones, Corrientes, Entre Rios (Argentina), Canindeyú, Alto Paraná, Itapúa, Misiones, Ñeembucú (Paraguay), Rio Grande do Sul, Paraná and Mato Grosso (Brazil) are extensively exploited by the Jesuit missions. To illustrate this, we must point out that such provinces are, at that time, more densely inhabited than the national capitals of Asuncion and Buenos Aires (Bravet 1768; de Massy 2010; Furlong 1937; Haubert 1986; Laborie and Lima 1998; Lacombe 1993; Levington 2008; Levington 2009; Lugon 1970). We shall not develop the specific modes of land clearing in the Jesuits reductions here, but it is worth mentioning the type of land use that they have generated. The production suits the general characteristics of the region, developing a trading waterway system between the colonies. The main products that may have led to a destabilisation of the soils, by slash and burn, were no doubt the substantial crops of Yerba mate, wheat, sorghum and other cereals (Levington 2007, 2009). No surface areas of cultivated land have been accurately calculated, but the Yerba-mate crops could have reached many acres in the small missions (500 inhabitants) (Levington 2007).

For now, we are still lacking some field evidence in order to confirm this hypothesis with certainty. This should be done in the future, by searching paleoforms of deforestation and vertical erosion on the field. Current literature shows that these mechanisms are possible. In an article dated 2009, Latrubesse et al. demonstrated similar processes on the River Araguaia in Brazil, whose watershed is affected by deforestation due to soya exploitation (Latrubesse and Amsler 2009). In this large alluvial river, the analysis show a morphological alteration in sediment budgets and a significant response of the river, which acquires a braided pattern. On the upper basin, linear forms of erosion are recorded (Carstro and de Campos 1999). The middle course shows a trend of cluttering which indicates a rapid adjustment of the river, in response to the deforestation. It has also been shown that the period of fluvial system response to human disturbance is close to a decade. If we consider this response period, it is possible to assert that the changes brought by land clearing in the Upper Paraná have been recorded in the old cartography.

The system response

What are then the parameters that define the system response? The methods are commonly used on small and medium-sized rivers. They take into account many parameters, the

Fig. 13 **a** Map of localisation of the gauging stations related to the synthesis table of the data needed to ▶ calculate the specific power, and **b** Specific powers on the different sections of the Paraná river. The width of the boxes drawned correspond to the importance of the specific power whereas their length symbolise the length of the considered section

values of which are not available for the Paraná river. The fact that very few measures are available in the Paraná watershed has acted in favour of a single and easily calculable parameter, that enable us to evaluate how the system responds to modifications in flow and in sediment quantity. We then need a parameter that allows us to determine sections with the most intense dynamics and those where sediments are stored. To accomplish this task, our field work allowed to obtain flow values in various gauging stations as well as the calculation of the slope[1] separating these measuring stations, which are often several hundred of kilometers apart. The records must then be integrated into a synthetic parameter that can be extrapolated to the sections that are not monitored precisely. We have therefore decided to consider the specific power,[2] which allows the river response to be quantified. If the values of specific power are close enough to a threshold then a small variation in the sediment load would allow the river to change its pattern. By using specific power we try to validate the possibility of changes in the Parana river with a small variation of the solid load, i.e., knowing the value of the specific power in each section, we can identify if the hypothesis of modification of the pattern is realistic over a century. According to Schumm (1981) if the slope is controlled by the substrate, as it is in the Upper Parana, and if Qs increases and Ql remains constant, the bed widens and there is an accumulation in the fluvial bed. The river planform is then transformed into a braided pattern. The values of specific power to develop a braided pattern are very low (generally included between 10 and 20 $\mathrm{W/m^2}$). The specific power is thus an objective characterisation of the fluvial pattern and the equations allow to hypothesise its potential of adjustment.

$$W = (\rho g \times \mathbf{Qpb} \times p)/\,l\left(\mathrm{W/m^2}\right)$$

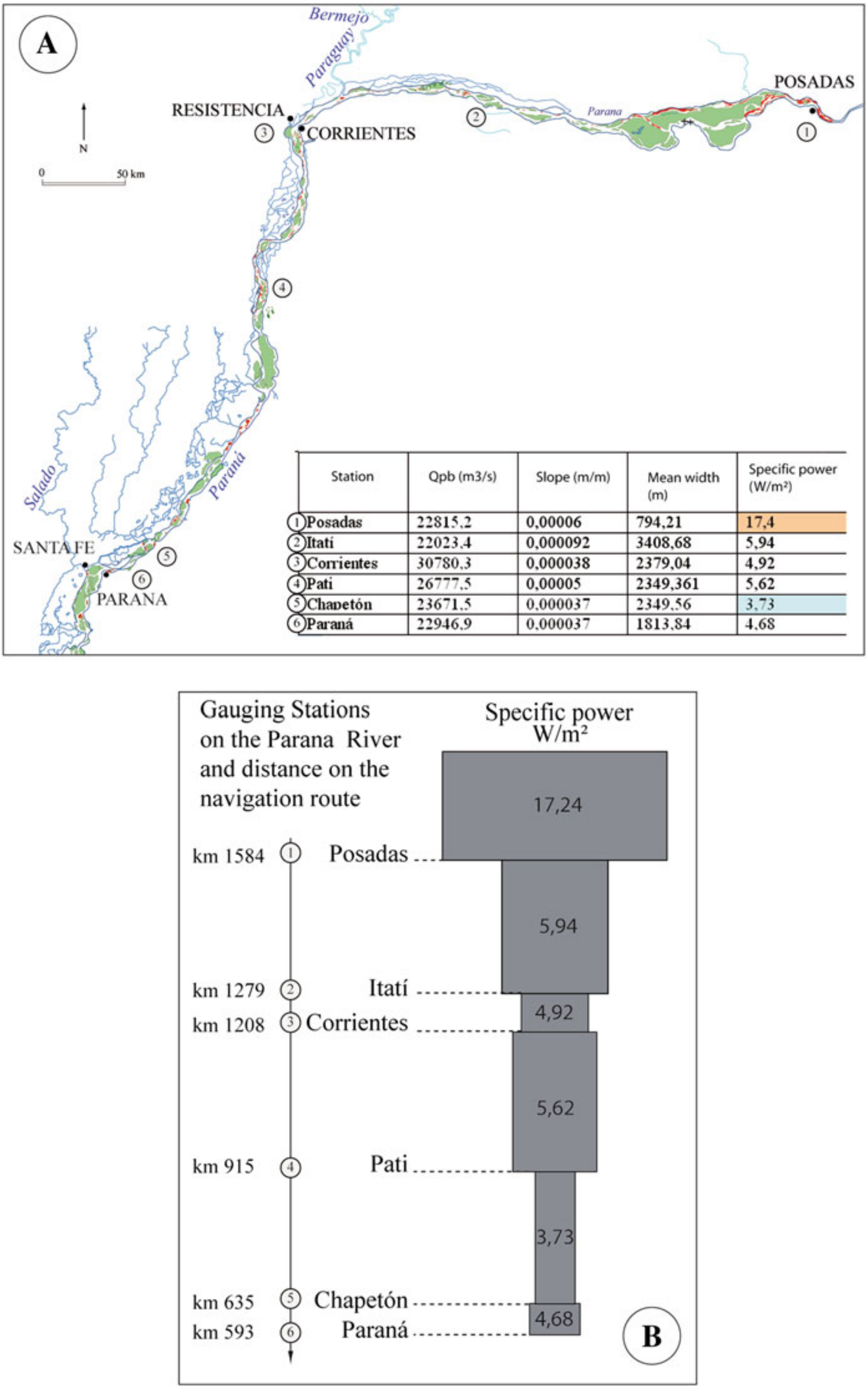
(Bravard and Petit 2000), with Qpb ($\mathrm{m^3/s}$) = flow with a return period of 1.5 years (Gumbel's curve), p (m/m): slope, ρg: constant, l (m): average width of the section (during high water).

The current specific powers (1906–2009) are quite low and almost constant over the entire course of the Argentinian Paraná, not even reaching 10 $\mathrm{W/m^2}$ (Fig. 13a). According to Nanson and Croke (1992) for specific powers less than 20 $\mathrm{W/m^2}$, the river pattern is rather meandering than braided. Indeed, the specific power affects the sediment transportation ability. In the case of the Paraná river, the sediment load is a significant variable given the low flowpower of the river. Its planform is easily modified by a small change in the sediment budget.

The power and specific-power values are represented in Fig. 13b which shows the distribution of powers in the different sections. The section of the Upper Paraná river is characterised by shallow slopes, shallow depths and low sinuosity channels. These characteristics seem consistent with the braided pattern observed in the eighteenth-century map, given that its specific power is very close to the threshold separating the braided and the meandering pattern (Nanson and Croke 1992). We can consider that the flow of the

[1] The slope of the river was measured according to the zeros of the local hydrometric scales.

[2] The specific power is the result of the combination of the values of slope and flow divided by the width of the channel. It allows to quantify the potential energy of a cut section of the channel, the width of the river conditioning the acceleration of the flow ($\mathrm{W/m^2}$).



Station	Qpb (m3/s)	Slope (m/m)	Mean width (m)	Specific power (W/m²)
1 Posadas	22815,2	0,00006	794,21	17,4
2 Itatí	22023,4	0,000092	3408,68	5,94
3 Corrientes	30780,3	0,000038	2379,04	4,92
4 Pati	26777,5	0,00005	2349,361	5,62
5 Chapetón	23671,5	0,000037	2349,56	3,73
6 Paraná	22946,9	0,000037	1813,84	4,68

Paraná river has not changed considerably since the XVIIIth century, given that neither on the field, nor on the old maps have been detected channels with greater dimensions. With an equivalent liquid flow, the variables have adjusted by increasing its sinuosity and depths, decreasing its slope and narrowing of the main channel. The system response is quick; the most sensitive sections often have a mixed style that can adjust rapidly to changes in sediment load associated with climatic and anthropogenic phenomena.

Conclusions

The results outlined in this article are only the first step in a work in progress. The hypothesis as to the change of origin of the sediment load and the change in planform of the Paraná river over the centuries should be implemented by obtaining absolute dating in the very heart of the islands.

A study of the structure of ancient islands would probably materialise the legacies of the eighteenth century, through the sizes of the sediment particles and their heterogeneous composition. The projected granulometric study would involve comparing the current sediment bedload of the Paraná River and those on the main deposit areas. These studies, however, require heavy logistics and funding. Besides, manual drillings could be performed in the islands and the inherited paleochannels. It is also possible to consider OSL dating of different samples. This method would provide absolute proof. Other methods are also possible such as the 210 Pb or 14C although they are more difficult to apply in the Paraná river environment.

The usefulness of this work is quite clear. The Parana river has changed since the XVIIIth century. With the construction of a lot of small dams in the Brazilian watershed and two large size dams (Yacyreta and Itaipu) and with the development of inland navigation which leads to a high demand of dredging. These interventions perturb the natural sedimentary transport in the main channel. This study is important for establishing long term baseline informations against which engineering intervention can be measured.

In conclusion, it is possible to emphasise the importance of data from old maps, which, thanks to a comparative analysis, have allowed a change in the functioning of the Paraná river to be identified. Field knowledge and validation of the reliability of old documents are two key elements to the proper use of the data. We can therefore say that despite their obsolescence, old maps can be successfully used to complement current research on large alluvial rivers.

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References

Amsler M (2006) Evolución de la carga de lavado en el alto Paraná (1968–2004). Incidencia sobre las sedimentaciones en la planicie aluvial del Paraná Medio, Actas III Congreso Iberoamericano sobre Control de la Erosión y los Sedimentos. Buenos Aires, Argentina

Amsler M, Drago E (1999) A review of the suspended sediments budget at the confluence of Paraná and Paraguay rivers symposium on hydrological and geochemical processes in large-scale river basins. Manaus, Brazil

Amsler M, Drago E (2007) A review of suspended sediment budget at the confluence of the Paraná and Paraguay Rivers. Hydrolog Process, Corrientes

Amsler M, Prendes H (2000) Transporte de sedimentos y procesos fluviales asociados. In: Paoli C, Schreider M El Río Paraná en su tramo medio. Centro de Publicacions Universitarias, Universidad Nacional del Litoral, Santa Fe, Argentina, pp 233–306

Angleria MP (1518) Decadas Océanicas. Fuentes Historicas sobre Colon y America. J Torres Asensio, Madrid, p 1892

Azara FD (1998) Viaje por la América Meridional. El Elefante Blanco, Buenos Aires, p 490

Bonetto A, Orfeo O (1984) Caracteres sedimentologicos de la carga en suspension del rio Paraná entre Confluencia y Esquina (Prov. Corrientes). Revista de la Asociacion de Minerologia, Petrologia y Sedimentologia 15(3–4):51–61

Bossi B (1863) Viage pintoresco por los ríos Paraná, Paraguay, San Lorenzo, Cuyabá y el Arino tributario del grande Amazonas con la descripción de la provincia de Mato Grosso bajo su aspecto físico, geográfico, mineralójico y sus producciones naturales. Librairie Parisienne, Paris

Bravard J-P (1989) Cartography of rivers in France. In: Petts G (ed) Historical changes of large alluvial rivers. Wiley, London, pp 95–111

Bravard JP (2011) La valorisation de la cartographie historique des rivières d'Europe, de la recherche sur la dynamique des paysages à la gestion des eaux. Il Paesaggio dei Technici, Attualità delle cartografia historica per il governo delle acque. Cremona 2008, Bologna

Bravard JP, Petit F (2000) Les cours d'eau. Armand Colin, Paris, p 222

Bravet (1768) Le Paraguai jésuite ou description succinte des terres dont les jésuites espagnols se sont emparés dans l'Amérique Méridionale…extrait fidellement des Mémoires de sieur Bravet, ingénieur à la Martinique, que ces Pères firent généralissime de leurs troupes dans la guerre contre les Xaraïes, en 1718, Bibliothèque nationale de France, département Réserve des livres rares, 8-OL-752

Broc N (1986) La géographie de la Renaissance. Ed. du Comité des Travaux historiques et Scientifiques, Paris, p 258

Broc N (1999) Dictionnaire illustré des explorateurs et grands voyageurs français du XIXème Siècle. Ed. CTHS, Paris, p 364

Carignano C (1997) CaracterizacioH n y EvolucioH n, durante el Cuaternario Superior, de los ambientes geomorfologicos en el noroeste de la provincia de Cordoba, Doctoral Thesis, Unpublished

Carstro S, de Campos AB et al (1999) The upper Araguai basin and the effect of human-induced erosion. Boletim Goiano de Geografia 19(1):128–139

Cioccale MA (1999) Climatic fluctuations in the central region of Argentina in the last 1000 years. Quater Int 62:37–45

De Blij HJ, Muller PO (1993) Physical geography: the global environment. Wiley, New York, p 576

de Massy RC, Levington N (2010) Un pueblo llamado Jesus. Fundacion Paracuaria Missionsprokur, Asuncion, Paraguay, p 95

d'Orbigny A (1835–1847). Voyage dans l'Amérique méridionale (le Brésil, la République orientale de l'Uruguay), exécuté dans les années 1826, 1827 et 1833. Pitois-Levrault; Strasbourg, Paris, Levrault

Drago E (1977) Erosion y sedimentacion en un tramo del cauce del Rio Paraná Medio. Revista Geologica Aregntina XXXII(4):277–290

Drago E, Amsler ML (1981) Sedimentos suspendidos en el tramo medio del Rio Paraná: variaciones temporales e influencia de los principales tributaries. Revista de la Asociacion de Ciencias Naturales del Litoral 15:1–6

Echaurri G (1739) Autobiografia. Asuncion

Federzoni L (2006) Marco Antonio Pasi a Ferrara, Cartografia e governo del territorio al crepuscolo del Rinascimiento. Istituto Geografico Militare, Rivista L'Universo, Florence, p 204

Furlong CG (1937) Cartografia Jesuitica del Rio de La Plata. Pub Inst de Inv Hist LXXI:125

Gurnell A, Peiry J-L et al (2005) Using historical data in fluvial geomorphology. In: Kondolf M, Piegay H (eds) Tools in fluvial geomorpholy. Wiley, Chichester, pp 77–99

Haubert M (1986) La vie quotidienne des indiens et des Jésuites du Paraguay au temps des Missions. Hachette, Paris, p 310

Hickin EJ (1984) Vegetation and river channel dynamics. Can Geogr 28(2):111–126

Hinchliff TW (1863) South American sketches: or, a visit to Rio Janeiro, the organ mountains, La Plata, and the Paranà. Longman, Green, Longman, Roberts, & Green, London

Hooke JM, Kaine JP (1982) Historical changes in the physical environment: a guide to sources and techniques. Butterworth, London

Iriondo MH, Garcia NO (1993) Climatic variations in the Argentine plains during the last 18,000 years. Paleogeogr Paleoclim 101:209–220

Iriondo M, Krohling D (1995) El Sistema Eolico Pampeano. Comunicacion Museo Provincial Ciencias Naturales Florentino Ameghino 5(1):1–68

Itaipu B (2006) Relatorio referente a reuniao do board de consultores civis. Efeitos sedimentologicos no reservatorio da UHE Itaipu, Rapport interne s/n vol

Knight C (1866) Excerpt relating to the Paraná–Paraguay river system from the entry on the Argentine confederation. The English Cyclopaedia. http://www.bluemacaws.org/hist31.htm. Accessed 26 Oct 2010

Laborie J-C, Lima A (1998) La mission jésuite du Brésil: lettres & autres documents (1549–1570). Chandeigne, Paris, p 350

Lacombe R (1993) Guaranis et Jésuites : un combat pour la liberté, 1610–1707. Société d'ethnographie, Karthala, Paris, p 301

Latrubesse E, Ramonell CG (1990) La Formacion Algarrobito-Registro de la Pequefia Edad del ielo en la provincia de San Luis, Argentina, 2nd IGCP 281 Meeting, Quaternary Climates of South America. Spec. Publications, Medellin

Latrubesse E, Amsler M et al (2009) The geomorphologic response of a large pristine alluvial river to tremendous deforestation in the South American tropics: the case of the Araguai river (Brazil). Geomorphology 113(3–4):239–252

Levington N (2007) Yacyreta, una nueva significacion. Buenos Aires Entidad Binacional Yacyreta, Paraguay 283

Levington N (2008) La arquitectura Jesuitico-Guarani. Una experiencia de interracion cultural. Buenos Aires Fundacion Paracuria Missionsprokur, Paraguay

Levington N (2009) El espacio jesuitico Guarani, Asuncion Paraguay. Centro de Estudios Antropologicos de la Universidad Catolica, Paraguay, p 295

Lugon C (1970) La république des Guaranis 1610–1768: les jésuites au pouvoir. Economie et humanisme, Ed. Ouvrières, Paris, p 244

McCarthy TS, Ellery WN et al (1992) Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. Sedimentology 39:779–795

Nanson GC, Croke J (1992) A genetic classification of floodplains. Geomorphology 4:459–486

Orfeo O (1995) Sedimentologia del rio Paraná en el area de confluencia con el rio Paraguay. Universidad Nacional de La Plata, Geologia 286

Parish W (1839) Buenos Aires and the Provices of the Rio de la Plata. Henry Colburn, Londres

Peireira MS, Montagnini M et al. (2009) Disparidades de Evolucion y Transporte Sedimentario en Ensanchamientos Sucesivos del Rio Paraná. Cuarto Synopsium sobre Hydraulica de Rios. Hidráulica de Ríos, Salta

Pelletier M (2001) Cartographie de la France et du monde, de la Renaissance au Siècle des Lumières. Bibliothèque nationale de France, Paris 107

Pelletier M (2009) De Ptolémée à La Guillotière (XV–XVIè). Des cartes pour la France, pourquoi? comment? CTHS, Paris, p 175

Pinto MD (2008) Aménagements hydroélectriques et impacts sur la dynamique des flux d'eau et de sédiments. Le cas du haut Paraná, Brésil, Géographie. Université Lyon, Lyon, p 2304

Prieto M, Jorba RA (1990) Las anomalias climaticas en la Cuenca del Plata y NOA y sus consecuencias socioeconomicas. Siglos XVI–XVII y XVIII. Sep Leng Revista Argentina de Geografia 1:41–103

Ramonell CG, Montagnini M et al. (2008) Morphologic and sediment transport adjustments around artificial point construction in a large, meandering river (Bermejo, Argentina). In: Hulscher DJ River, coastal and estuarine morphodynamics: RCEM 2007. Taylor and Francis Group, London, pp 1143–1147

Riccardi C (1995) Paleoclimatologia Cambio Global. Esp Acac Nac de Geografia 10:91–126

Schmidel U (1942) Crónica del viaje a las regiones del Plata, Paraguay y Brasil. Peuser, Buenos Aires

Schumm SA (1971) Fluvial geomorphology: channel adjustment and river metamorphosis. In: Schem HW River mechanics. Fort Collins, Colorado, pp 5–22

Schumm SA (1977) The fluvial system. Wiley, New York, p 338

Smith DE (1981) Riparian vegetation and sedimentation in the braided river, Geography. Arizona State University, Arizona

Torre JR (1938) Mapas y planos referentes al virreinato del Plata conservados en al Archivo General de Simancas. Instituto de Investigaciones Historicas, Buenos Aires

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